THE RADIATION OF HEAT FROM THE HUMAN BODY

II. A Comparison of Some Methods of Measurement

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In this paper it is proposed to discuss some of the more usual methods for making measurements of skin temperature. Four instruments of different design have been tested under a variety of experimental conditions and the comparative results are offered with explanations of the differences which are found to exist between the several methods. The designs investigated are those of F. G. Benedict (1), G. F. Soderstrom (2), the Taylor Instrument Company (3), and the radiometer described in the preceding paper (4). These instruments are believed to be typical of the many devices which have been developed for this work, hence the conclusions drawn from the results of these tests are applicable generally to instruments of similar design.

Probably the most important work on the technique of measurement of surface temperature is that of Aldrich (5) who made comparative measurements of surface temperature with a surface thermocouple thermometer and with a radiation device. Recently Grassberger (6) has made some tests on the theory of thermocouple thermometers but his results do not include comparative data. The latest work on this subject is that by Bedford and Warner (7) who compared several surface thermometers with a radiometer by making measurements on the human forehead. Their conclusions are in general agreement with the present findings, although comparisons made on the skin surface have the obvious disadvantages mentioned below. Aldrich's experiments are so complete that they will be discussed here in detail in order to illustrate the difficulties encountered in the measurement of surface temperature. Aldrich made measurements on 20 persons using both the thermocouple and radiometer and his results showed that the readings of the thermocouple device were systematically *lower* than those of the radiometer by about 1.1° C. In a supplementary report (8) he endeavored to ascertain wherein this difference lay and his conclusion was that his thermocouple device was more to be trusted than his radiometric device. If one consider this disagreement from a physical standpoint there immediately arises an inconsistency. There can be no doubt but that Aldrich's radiometer (9) was actually measuring with sufficient precision the energy radiated from the skin or clothing. The question arises as to the whether or not he was justified in transforming, through the Stefan-Boltzmann equation, his radiometric energy values into surface temperatures which can be compared with those obtained from his thermocouple. One may examine this question in the following way:

The radiation formula which expresses the exchange of radiation between two bodies at different temperature is

$$Q = k\ e\ e'\ S_0(T^4 - T_0^4),$$

where, Q = the energy exchange,
k = proportionality factor depending upon the size, shape, and localities of the bodies,
e = absorbing power of the receiver,
e' = emitting power of the emitter,
S_0 = Stefan-Boltzmann constant,
T = Absolute temperature of the emitter,
T_0 = Absolute temperature of the absorber.

In Aldrich's radiation experiments all the constants of the equation were known except e' and T, and therefore if he were solving for T, the skin temperature, it would be necessary for him to assume a value for e', the emissivity of the skin. He based his calculations upon the assumption that the human skin is a perfect radiator, thus making $e' = 1$. If, however, he should substitute the values of T as determined by means of his thermocouple thermometer into the above equation and solve for e', it is obvious that e' would have a value greater than unity. This would indicate that the skin radiated more perfectly than an ideally perfect radiator. This, of course, as was recognized by Aldrich, is physically impossible. So far as I am aware, this is the only attempt to compare the radiometric method with the thermocouple method and it shows beyond question that Aldrich's thermocouple thermometer was not measuring the temperature of the surface from which the radiation was emanating. There seem to be only two interpretations of the matter, either the thermocouple thermometer was not reading the correct surface temperature, or the radiometer was reading the temperature of layers of tissue below the actual surface of the skin. This latter, indeed, is what Aldrich tentatively assumed to be the case, suggesting that the outer layers of the skin are transparent to infra-red light and that, therefore, the radiometer was " seeing " down into the deeper and warmer layers. He also suggested the possibility of the skin being so rough that the thermocouple could come in contact with only the outer, cooler, ridges, while the radiometer also averaged in the warmer " valleys." This latter suggestion seems hardly valid since one might expect to hit a valley about as often as a ridge and the differences therefore to be ironed out. The evidence as to the former suggestion is briefly reviewed below.

According to Bazett and McGlone (10) the tissue 4 mm. below the surface of the skin is about 1.1° C. warmer than the surface, therefore should the radiometer see down to approximately this depth the discrepancy observed by Aldrich might be accounted for. Aldrich, however, in a later report (8) finds that no infra-red light is transmitted through a layer of skin 2 mm. thick. The question of the infra-red absorption of skin is now under investigation in this laboratory by Dr. C. Muschenheim and myself, and our preliminary results indicate that 95 per cent of the infra-red beyond 5 μ is absorbed by a layer of skin 0.2 mm. thick. Thus if the radiometer were reading the temperature of the layers of tissue 0.2 mm. below the surface, we might expect that it would read 0.06° C. higher than a thermocouple which is reading the actual temperature of the surface. Thus it would seem from this work and that of others that the heat is conducted to the outer layers of the skin and radiated therefrom in the form of heat waves.

Another important point in connection with the estimation of skin temperature from radiation data is the value of e', the emissivity of the surface of the skin. This matter is taken up in detail in Part III of this series (12), and it will be sufficient here to say that all the evidence which has been obtained by others and myself indicates that the skin radiates so well as to be a perfect radiator within the error of measurement in such experiments. Therefore it would seem that the calculation of skin temperature from the unmodified Stefan-Boltzmann formula, once the energy has been correctly measured, is a legitimate procedure. That being the case, the fault in Aldrich's experiments must have been with his thermocouple thermometer and not with his radiation device. Having had already some evidence to support this thesis I repeated the experiment which had led Aldrich to the contrary conclusion. Aldrich's experiment is briefly described.

A copper calorimeter supplied with a stirrer and thermometer had three holes cut in its side and over these holes were cemented rubber diaphragms of thicknesses varying from 0.1 mm. to 1.2 mm. With his surface thermoelement applied to the outside of the diaphragms, Aldrich made readings of the temperature of the surface of the rubber membranes. These data, together with the thicknesses of the diaphragms and the temperature of the calorimeter water and room temperature, enabled him to plot diaphragm thickness, d, as abscissae, and, ΔT, the differences between two sides of the diaphragm, as ordinates, for various differences in temperature between the calorimeter and the room. The results of his measurements are shown in Figure 1, Curves A and B. Curve A represents the relationship when the difference between the calorimeter temperature and room temperature, $\Delta T'$, was 10° C.; Curve B when $\Delta T' = 5°$ C.

The theory of heat conduction leads one to expect the curve between diaphragm thickness and ΔT to be of the general shape shown by A and B, that is, an exponentially increasing ΔT which gradually approaches $\Delta T'$ as a limit for very large thicknesses of rubber. It is worthy of note, therefore, that for such small thicknesses of rubber, Curves *A* and *B* so rapidly approach their apparent limits and that these limits are so far removed from the actual values of $\Delta T'$. This evidence together with that before

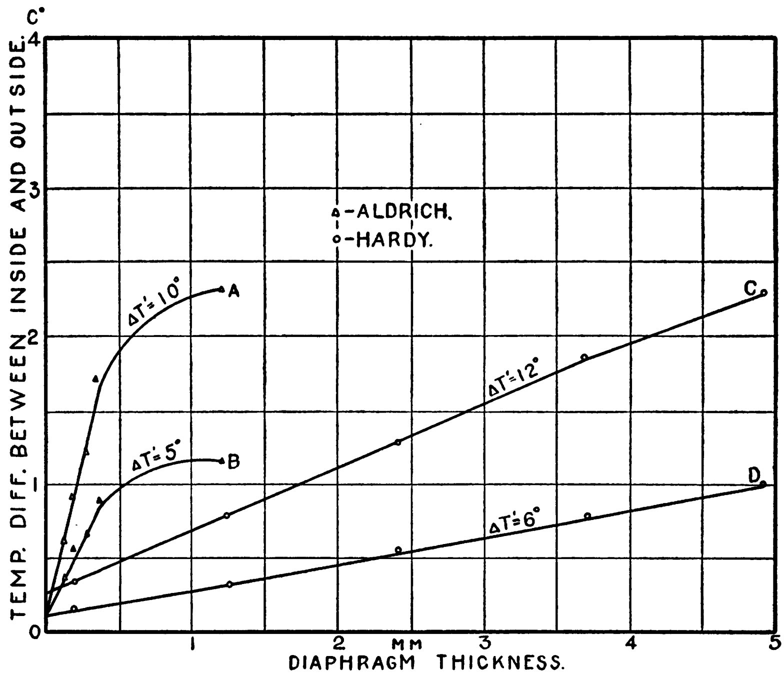

FIG. 1. RELATIONSHIP BETWEEN DIAPHRAGM THICKNESS AND TEMPERATURE DIFFERENCE BETWEEN INNER AND OUTER SURFACES OF THE DIAPHRAGMS. Curves *A* and *B* obtained by Aldrich; *C* and *D* obtained with radiometer.

mentioned made the repetition of the experiment seem worth while, and it was undertaken with the following differences: The diaphragm thicknesses were extended from 0.18 mm. to 5 mm. and the outside surface temperature was measured by means of the radiometer. The results are shown in the same figure, Curves *C* and *D*. The value of ΔT rises almost linearly with d until $d = 3.7$ mm. where indications of the exponential character of the curves begin to be manifest. An extrapolation of Curve *C* (with constant slope) would make $\Delta T = \Delta T'$ when $d = 25$ mm., whereas an extrapolation of Aldrich's Curve *A* would lead to the incongruous result of $\Delta T = 3°$ C. for very large thicknesses of rubber. Aldrich concluded from the fact that the extrapolated Curves *A* and *B* pass almost through the zero of ΔT for $d = 0$, that his thermoelements were reading the correct surface temperature, but while this is a necessary condition it is not a sufficient one and the slope of the curves may be changed at will by altering the external conditions.

It will be noticed that upon extrapolation to zero diaphragm thickness the Curves C and D do not pass through the point of zero ΔT, which means that the radiometer temperatures for the rubber are too low. This is due to the fact that rubber is not a perfect black-body. If, however, the curves be corrected for the emissive power of the rubber (0.98) they then pass through the zero point. The corrected curves give the true values of ΔT from which the surface temperature of the diaphragm can be determined. Upon comparing A and B with C and D, it will be seen that the thermoelement is indicating that rubber radiates more than a perfect black-body. An explanation of Aldrich's curves may be as follows: the too rapid rise in ΔT for thin diaphragms is probably due to the "calibration error" discussed below, an error which would tend to make the temperature readings too low; the too rapid sloping off of his curves is probably due to different conditions of thermal contact between the thicker rubber and his thermoelement. Experimental tests show that these two suggestions give approximately the right corrections to bring the thermocouple and radiometer into agreement.

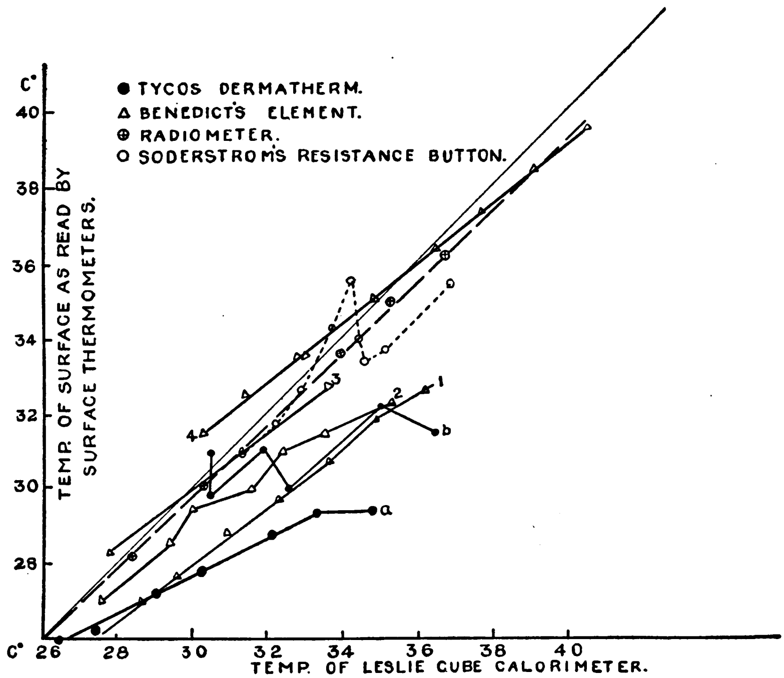

FIG. 2. TESTS OF SURFACE THERMOMETERS AGAINT A THIN RUBBER DIAPHRAGM

Having satisfactorily accounted for Aldrich's tests it became obvious that similar tests upon other designs of thermoelements were desirable in order to determine whether or not the matter of design was of major importance. Therefore the skin thermometers of Benedict, Soderstrom, and The Taylor Instrument Company were compared against the radiometer. These tests were made on the thinnest rubber diaphragm, the inside temperature of which was assumed to be that of the calorimeter water and the outside surface temperature was calculated from the experiment just described. The results are shown in Figure 2.

The calibrations of all the devices were checked before the tests, and the method of applying the thermometers to the diaphragm was varied so as to include several possibilities. The usual method, developed by Benedict, of first warming the thermometer with the thumb, then placing the element on one edge of the diaphragm and lastly slipping it over to the middle as soon as equilibrium was established, was considered standard.

The diagonal line represents the temperature of the surface of a hypothetical diaphragm of zero thickness; the broken curve gradually diverging from this line represents a corrected curve for diaphragm thickness 0.2 mm., and it is to this curve that all the other surface thermometers are referred. Four sets of values are given for Benedict's thermocouple (designated by the triangles). Number 2 represents a test at room temperature 23° C. and Number 4 at 33° C., using the standard method of application. (Curve Number 4 should be referred to the diagonal line rather than to the corrected curve which is valid only for temperatures near 23° C.) The effect of room temperature upon the readings of the Benedict thermometer is obvious. A great many tests were made with the Benedict element and it was found that the readings on the diaphragm could be changed almost at will by using different methods of applying the element. Curve 1, with Benedict's device, was obtained by clamping the element in contact with the diaphragm and then raising the temperature in the calorimeter. Curve 3 was obtained by keeping the device well heated in the closed palm of the hand between measurements but following the standard procedure as to the application of the device to the diaphragm. The effect of the temperature of the backing of the sensitive element is thus brought out. This emphasizes the point made by Benedict that a standard procedure of application be adopted, but it was found that even using such a procedure the readings were not consistent to better than $\pm$ 0.5° C. The irregular curves shown for the Tycos " Dermatherm " and the Soderstrom resistance button were obtained by warming the calorimeter and, after making a reading, cooling it down rapidly. The large heat capacities of the instruments are thus shown to cause a reading to be affected by the previous one, if the readings are made in the usual rapid manner. If the observations are made slowly enough the irregular character is much reduced and the instruments show qualitatively the same characteristics as the Benedict element, the " Dermatherm " showing larger errors and the resistance button somewhat smaller. Curve *"a"* for the " Dermatherm " was made by clamping the device to the diaphragm. The radiometer was tested many times under the same conditions as the surface thermometers and its readings showed good agreement (± 0.1° C.) each time.

The errors generally encountered in the use of skin thermometers might be classified as follows, errors due to calibration, errors due to manipulation and errors due to the effect of the instrument on the surface to be measured. The first two sources of error, while troublesome and probably present in the work of past observers, can be partially circumvented under special circumstances; the last source is inherent in the methods and while generally much smaller than the first two would probably prevent the methods from ever becoming precise. The magnitude of these combined errors may total as much as four or five degrees centigrade depending upon conditions.

The "calibration errors" refer to the errors induced in the measurements made by surface thermometers due to the difference between the calibrating and measuring conditions. This error is believed by the present author to be the largest of the three mentioned above. The usual calibration procedure for surface thermometers is that of comparing the surface thermometer and a standard thermometer while submerged in some liquid. The thermal-junction is then surrounded by the liquid on all sides and is certainly at the temperature of the liquid (and of the standard thermometer) as the calibration is carried on. When the instrument is brought out for use in the measurement of skin temperatures the conditions are widely different from those of the calibration. In this latter case only a part of the sensitive element of the thermometer is in contact with the skin while the remainder is either in contact with the cool room air, as in Aldrich's device, or in contact with some other surface generally cooler than the skin, as in the Benedict and Tycos devices. It is evident that the thermocouples will assume a temperature somewhere between that of the skin and that of the external medium and therefore will not measure the true surface temperature. This probably accounts for the fact that the usual surface thermometer gives temperatures lower than that of the radiometer. This error should be systematic if sufficient precautions are taken to eliminate other sources of error and the surface thermometer should be expected to be in error by about — 1.0° C. when used at a room temperature of 20° C. to 25° C. The error may become positive when the thermometers are used at high room temperatures, and also at low room temperatures when certain methods of application are used.

Errors due to manipulation are those arising from the fact that the equilibrium point of the thermometer depends, among other things, upon room temperature, the excellence of the thermal contact (pressure with which the element is pressed against the surface, moisture of skin, etc.) design of instrument, method of applying the thermometer, etc. These errors are probably small when one person is making readings under a given set of conditions with a given instrument in a given manner, but they become very much larger when measurements are to be made for comparison in other laboratories when using a different or even the same instrument. This fact makes the work of any single observer unique, not amenable to check or confirmation, and reduces the value of skin temperature measurements to simple experiments of differentiating a hot spot on the skin from a cold one qualitatively. It is recognized that such measurements are now made and are of value clinically. However, a systematic investigation of value to all observers is not possible using the usual skin thermometer, and it might be for this reason that the temperature of the skin is scientifically of no more value than it is at present.

The errors due to the effect of the instrument on the skin are hard to separate from the two former. They have been discussed by Cobet and Bramigk (11) and by Bazett and McGlone (10), but it is probable that this is the smallest source of error when using devices of small heat capacity.

It is not the purpose of this article to condemn the time-honored methods for making measurements of skin temperature, but rather to present them in their true light to indicate those fields for which they are best suited. The general ruggedness and simplicity of these instruments make them ideal for experiments that do not require a relative accuracy greater than ± 0.5° C. or an absolute accuracy greater than ± 1.0° C. Recognizing these general limitations the fields of investigation to which the several methods are applicable become clear, and investigators can choose an instrument which will best fit the case.

The experimental material included in this paper is not regarded as absolutely conclusive in regard to the accuracy of the skin thermometers for the very reason that the data are taken from a rubber diaphragm and not the skin. However, the evidence gained therefrom, taken together with the difficulties discovered by Aldrich, point to the fact that there is little to be expected from the difference between the skin and the rubber diaphragm. The skin does not make a good surface upon which to test instruments of this kind because its temperature is not known independently and its temperature is not constant either as to time or locality. The thin rubber membrane, on the other hand, simulates the skin surface and its temperature is constant over its surface for a sufficient length of time to make tests. Furthermore, the surface temperature is known (even without corrections for diaphragm thickness) to a sufficient accuracy and can be controlled for testing purposes. Many tests of the skin thermometers were made, however, on the skin and compared with measurements made with the radiometer. The results of these tests confirmed the observations of Aldrich when the tests were made at room temperatures near 23° C. It was found that by using various methods of applying the thermometers, thermocouple readings were obtained either higher or lower than the radiometer readings. This was particularly true of all instruments which had more or less massive coverings to their sensitive elements, i.e. the Benedict, Soderstrom, and Tycos elements. The tests on the skin, however, can only indicate whether or not the skin thermometers are in agreement but do not give any clue as to which instruments are reading accurately the skin temperature. The evidence whether obtained from the skin or from the rubber diaphragm is in complete agreement as far as this most important question is concerned, and supports in every detail the conclusions enumerated above.

SUMMARY AND CONCLUSIONS

1. A repetition of the studies of Aldrich indicates that the discrepancies between his radiometer and skin thermometer readings were due to errors in the thermocouple thermometer, these errors being inherent in all skin thermometers which depend on contact with the skin surface.

2. The results of tests on the surface thermometers of F. G. Benedict, G. F. Soderstrom, and the Taylor Instrument Company show that the thermometers read too low by 1° C. to 3° C., depending upon conditions, when used at room temperatures in the neighborhood of 20° C. The tests show also that the reproducibility for the skin thermometers is in general about ± 0.5° C. and this error may run as high as ± 5° C. if readings are not made under uniform conditions with a standard technique.

3. The errors in measurements of skin temperature made by the usual type thermometer are classified as "calibration errors," "manipulation errors," and errors due to the effect of the instrument on the skin. It is concluded from a consideration of these errors that a relative accuracy of ± 0.5° C. and an absolute accuracy of ± 1.0° C. is the best that can be expected from instruments of similar design.

4. Skin temperature measurements with a radiometric device are shown to be accurate both relatively and in absolute value to ± 0.1° C.

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